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Predicting In-Flight MAD Noise From Ground Measurements

J. Bradley Nelson

Defence R&D Canada

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Defence Research Establishment Atlantic

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Abstract

In the past, determining the magnetic state of magnetic anomaly detector (MAD)-equipped aircraft required dedicated flight time. It was necessary to perform standard pitch, roll, and possibly yaw maneuvers to measure the uncompensated Figure-of-Merit in order to determine if the aircraft's magnetic state had changed. This change could have been caused by ferrous material left in the vicinity of the magnetometer during an aircraft refit, replacement of the MAD sensor, or large-scale modifications to the aircraft or its systems.

A new technique using only a few measurements taken on the ground at a magnetically quiet site (e.g. a Compass Rose) has been developed to monitor the magnetic state of MAD-equipped aircraft. The technique, first suggested by CAE, was used to model the permanent and induced magnetic sources on the National Research Council Convair 580 aircraft and to predict the in-flight MAD noise. Although the predicted noise amplitudes do not match the measured amplitudes for individual aircraft maneuvers, the standard deviations agree to within a few percent when calculated over a full set of compensation maneuvers. Thus the ground measurements can be used as an indicator of the degree of magnetic contamination in the aircraft.

This technique could be adapted to monitor the magnetic characteristics of both the Canadian Forces CP-140 and CH-124B fleet, and to conduct a number of MAD-related experiments at a minimal cost.

Résumé

Par le passé, la détermination de l'état magnétique d'un aéronef équipé d'un détecteur d'anomalie magnétique (MAD) exigeait du temps de vol spécial. Il fallait exécuter des manœuvres standard en tangage, en roulis et, éventuellement, en lacet pour mesurer le facteur de mérite non compensé, afin de déterminer si l'état magnétique de l'aéronef avait changé. Ce changement aurait pu être causé par du matériau ferreux laissé à proximité du magnétomètre pendant la remise en état de l'aéronef, le remplacement du capteur MAD ou des modifications majeures de l'aéronef ou de ses systèmes.

Une nouvelle technique faisant appel à quelques mesures seulement effectuées au sol, à un emplacement présentant peu d'activité magnétique (p. ex. à une rose-compas) a été élaborée pour surveiller l'état magnétique d'un aéronef équipé d'un MAD. Cette technique, suggérée à l'origine par CAE Électronique Ltée, a été utilisée pour modéliser les sources magnétiques permanentes et induites à bord de l'aéronef Convair 580 du Conseil national de recherches du Canada et pour prédire le bruit

MAD en vol. Bien que les amplitudes prédites du bruit ne correspondent pas aux amplitudes mesurées pour les manœuvres individuelles de l'aéronef, les écarts types concordent à quelques pour cent près lorsqu'ils sont calculés pour une série complète de manœuvres de compensation. Par conséquent, les mesures au sol peuvent être utilisées comme un indice du degré de contamination magnétique de l'aéronef.

Cette technique pourrait être adaptée pour surveiller les caractéristiques magnétiques des flottes de CP-140 et de CH-124B des Forces canadiennes et pour mener un certain nombre d'expériences en rapport avec le MAD à un coût minime.

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Executive summary

Background: Although the automatic compensation systems on the ASQ-502 and ASQ-504 magnetic anomaly detection (MAD) systems are extremely effective at removing aircraft-generated noise, there are certain times when the systems may not be as effective as expected. This may be due to ferrous material left near the magnetometer during an aircraft refit, accidental magnetization of components near the sensor when touched by magnetized tools, or problems with the sensing head. In the past, determining if this noise was due to excess magnetic contamination in the aircraft required dedicated flight time. It was necessary to perform standard pitch, roll, and possibly yaw maneuvers to measure the uncompensated Figure-of-Merit in order to determine if the aircraft's magnetic state was significantly different from normal. A new technique using only a few measurements taken on the ground at a magnetically quiet site (e.g. a Compass Rose) has been developed by CAE and DREA to monitor the magnetic state of MAD-equipped aircraft. The technique was used to model the permanent and induced magnetic sources on the National Research Council Convair 580 aircraft and to predict the in-flight MAD noise. This prediction was then compared to the actual measured MAD noise during a set of compensation maneuvers.

Significant Results: Although the predicted noise amplitudes did not match the measured amplitudes for individual aircraft maneuvers, the standard deviation of the predicted in-flight MAD noise in the band 0.1-0.8 Hz agreed with that of the measured in-flight noise to within a few percent. Thus the ground measurements can be used as an indicator of the degree of magnetic contamination in the Convair aircraft. The predicted heading dependence of the aircraft's DC total-field closely matched what was measured. The largest errors occurred, as expected, during turns when the effect of the terms not included in the ground model have the most effect. The in-flight noise prediction converged rapidly and only a small number of ground measurements were required before there was no improvement in the quality of the prediction. In order to more easily apply the method to the Canadian Forces fleet of MAD-equipped aircraft, some modifications to the ground measurement methodology have been suggested. A number of potential applications for the method have been identified.

Future Work: The method should be tested on a number of aircraft types, using a base station to record the temporal variations in the Earth's field. The horizontal positioning errors should be reduced or corrected for using DGPS and measured horizontal gradients. Care should be taken to avoid magnetic noise from ground personnel. In this way, it may be possible to use the coefficients measurement on the ground to more accurately predict the noise due to individual manoeuvres, not just the overall standard deviation of the manoeuvre noise. This would make the technique more useful for detailed magnetic contamination studies.

Sommaire

Contexte : Bien que les systèmes de compensation automatique des détecteurs d'anomalie magnétique (MAD) ASQ-502 et ASQ-504 soient extrêmement efficaces pour éliminer le bruit magnétique produit par l'aéronef, il y a des cas où ils ne sont pas aussi efficaces que prévu. Cela peut être causé par du matériau ferreux laissé à proximité du magnétomètre pendant la remise en état de l'aéronef, par la magnétisation accidentelle d'éléments à proximité du capteur touchés par des outils magnétisés ou par des problèmes de la tête de détection. Par le passé, pour déterminer si ce bruit était causé par une contamination magnétique excessive de l'aéronef, il fallait du temps de vol spécial. Il fallait exécuter des manœuvres standard en tangage, en roulis et, éventuellement, en lacet pour mesurer le facteur de mérite non compensé, afin de déterminer si l'état magnétique de l'aéronef différait notablement de la normale. Une nouvelle technique faisant appel à quelques mesures seulement effectuées au sol, à un emplacement de l'aéronef présentant peu d'activité magnétique (p. ex. à une rose-compas), a été développée par CAE Électronique Ltée et le CRDA pour surveiller l'état magnétique d'aéronefs équipés d'un MAD. Cette technique a été utilisée pour modéliser les sources magnétiques permanentes et induites à bord de l'aéronef Convair 580 du Conseil national de recherches du Canada et pour prédire le bruit MAD en vol. Cette prédiction a ensuite été comparée avec le bruit MAD mesuré pendant une série de manœuvres de compensation.

Résultats significatifs : Bien que les amplitudes prédites du bruit ne correspondent pas aux amplitudes mesurées pour les manœuvres individuelles de l'aéronef, l'écart type du bruit MAD prédit dans la bande de 0,1-0,8 Hz concordait avec celui du bruit mesuré en vol à quelques pour cent près. Par conséquent, les mesures au sol peuvent être utilisées comme un indice du degré de contamination magnétique de l'aéronef Convair. La dépendance prédite du cap du champ électrique continu total de l'aéronef correspondait de près aux valeurs mesurées. Les erreurs les plus grandes se sont produites, tel que prévu, lors des virages, où les non compris termes dans le modèle au sol ont le plus d'effet. La prédiction du bruit en vol convergeait rapidement, et il suffisait d'un petit nombre de mesures au sol avant qu'il n'y ait plus d'amélioration de la qualité de la prédiction. Pour faciliter l'application de la méthode à la flotte d'aéronefs équipés de MAD des Forces canadiennes, certaines modifications des méthodes de mesure au sol sont suggérées. Un certain nombre d'applications potentielles de la méthode sont identifiées.

Futurs travaux : La méthode devrait être mise à l'essai sur un certain nombre de types d'aéronefs, tout en faisant appel à une station de base pour enregistrer les variations temporelles du champ magnétique de la Terre. Les erreurs de positionnement horizontal devraient être réduites ou compensées au moyen du DGPS et de gradients horizontaux mesurés. Il faut avoir soin d'éviter le bruit magnétique causé par le personnel au sol. De cette façon, il pourrait être possible d'utiliser la

mesure des coefficients au sol pour prédire avec plus de précision le bruit dû aux manœuvres individuelles, et non simplement l'écart type global du bruit des manœuvres. Cela rendrait la technique plus utile pour des études détaillées de contamination magnétique.

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Prédiction du bruit MAD en vol à partir de mesures au sol
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1. Introduction

Although the automatic compensation systems on the ASQ-502 and ASQ-504 magnetic anomaly detection (MAD) systems are extremely effective at removing aircraft-generated noise, there are certain times when the systems may not be as effective as expected. This may be due to ferrous material left near the magnetometer during an aircraft refit, accidental magnetization of bolts, screws, or control cables near the sensor when touched by magnetized tools, or problems with the sensing head. In the past, determining if this noise was due to excess magnetic contamination in the aircraft required dedicated flight time. It was necessary to perform standard pitch, roll, and possibly yaw manoeuvres to measure the uncompensated Figure-of-Merit in order to determine if the aircraft's magnetic state was significantly different from normal.

A new technique using only a few measurements taken on the ground at a magnetically quiet site (e.g. a Compass Rose) has been developed by CAE (Ref 1) and DREA to monitor the magnetic state of MAD-equipped aircraft. The technique was used to model the permanent and induced magnetic sources on the National Research Council Convair 580 aircraft and to predict the in-flight MAD noise. This prediction was then compared to the actual measured MAD noise during a set of compensation manoeuvres.

Section 2 describes the mathematical foundation for estimating the in-flight noise from ground measurements. Sections 3 and 4 describe the measurement techniques and compare the predicted to the measured in-flight noise. Sections 5 and 6 describes how this method could be adapted to monitor the Canadian Forces fleet of CP-140 and CH-124 aircraft and simplify other MAD-related experiments.

2. Mathematical Model for Aircraft Magnetic Sources

Leliak (Ref 2) first described how permanent, induced, and eddy current sources on a MAD-equipped aircraft could be modeled using only the direction cosines for pitch, roll, and heading, and an estimate of the total-field. This model was adapted to use the three components of the Earth's magnetic field as measured by a fluxgate magnetometer mounted near the MAD sensor instead of the direction cosines (Ref 3). This model now forms the basis of the CAE compensation algorithm.

The total-field noise generated at the MAD sensor from all the permanent magnetic sources on the aircraft can be modeled by the terms:

$$\text{Term } 1 = C_1 \times T/He \ , \qquad [1a]$$
$$\text{Term } 2 = C_2 \times L/He \ , \text{ and} \qquad [1b]$$
$$\text{Term } 3 = C_3 \times V/He \ , \qquad [1c]$$

where T,L,V are the transverse, longitudinal, and vertical components of the Earth's field respectively, C_i are unknown coefficients, and $He = \sqrt{(T^2 + L^2 + V^2)}$. Similarly, the total-field noise generated at the MAD sensor from all the induced magnetic sources on the aircraft can be modeled by the terms:

$$\text{Term } 4 = C_4 \times T \times T/He \ , \qquad [1d]$$
$$\text{Term } 5 = C_5 \times T \times L/He \ , \qquad [1e]$$
$$\text{Term } 6 = C_6 \times T \times V/He \ , \qquad [1f]$$
$$\text{Term } 7 = C_7 \times L \times L/He \ , \qquad [1g]$$

$$\text{Term 8} = C_8 \times L \times V/He \ , \text{ and} \qquad [1h]$$
$$\text{Term 9} = C_9 \times V \times V/He \ . \qquad [1i]$$

Finally, the total-field noise generated at the MAD sensor from eddy currents generated in all the conductive surfaces on the aircraft can be modeled by the terms:

$$\text{Term 10} = C_{10} \times T \times T'/He \ , \qquad [1j]$$
$$\text{Term 11} = C_{11} \times T \times L'/He \ , \qquad [1k]$$
$$\text{Term 12} = C_{12} \times T \times V'/He \ , \qquad [1l]$$
$$\text{Term 13} = C_{13} \times L \times T'/He \ , \qquad [1m]$$
$$\text{Term 14} = C_{14} \times L \times L'/He \ , \qquad [1n]$$
$$\text{Term 15} = C_{15} \times L \times V'/He \ , \qquad [1o]$$
$$\text{Term 16} = C_{16} \times V \times T'/He \ , \qquad [1p]$$
$$\text{Term 17} = C_{17} \times V \times L'/He \ , \qquad [1q]$$
$$\text{Term 18} = C_{18} \times V \times V'/He \ , \qquad [1r]$$

where the ' denotes time derivative. Thus the full model for aircraft-generated MAD noise has 18 unknown coefficients C_i and 18 measured quantities derived from the vector magnetometer outputs. This model does not include any hysteresis or temperature-dependent effects.

Note there are two relations that can be used to reduce the model to only 16 terms for bandpass filtered signals. The first is:

$$He^2 = T^2 + L^2 + V^2 \qquad [2a]$$

As He ~ constant, bandpass filtering the LHS gives zero. Re-arranging yields

$$V \times V/He = -(T \times T/He) - (L \times L/He) \ . \qquad [2b]$$

Thus
$$\text{Term 9} = C_9 \times V \times V/He$$
$$= -C_9 \times [(T \times T/He) + (L \times L/He)]$$
$$= -(C_9/C_4) \times (\text{Term 4}) - (C_9/C_7) \times (\text{Term 7}) \ . \qquad [2c]$$

Similarly,

$$(He^2)' = (T^2 + L^2 + V^2)' \qquad [3a]$$

or
$$He \times He' = TT' + LL' + VV' \ . \qquad [3b]$$

Because He is almost constant, it follows that He' ~ 0 and

$$(T \times T'/He) + (L \times L'/He) \sim -(V \times V'/He) \qquad [3c]$$

or
$$\text{Term 18} \sim -(C_{18}/C_{10}) \times (\text{Term 10}) - (C_{18}/C_{14}) \times (\text{Term 14}) \ . \qquad [3d]$$

The 16-term model (no Term 9 or 18) is used in both the ASQ-502 and ASQ-504 systems for bandpass-filtered aircraft compensation.

When the aircraft is flying, small attitude changes excite the various terms and generate MAD noise. In order to accurately calculate the unknown coefficients C_i, it is necessary to execute small manoeuvres on several headings - either with dedicated manoeuvres for the ASQ-502 or with naturally occurring aircraft motions for the ASQ-504. These coefficients will accurately represent the magnetic state of the aircraft for a prolonged period of time.

However, the problem that is being addressed here is to estimate the in-flight MAD noise, not to accurately determine the 16 unknown coefficients. Can we use a reduced model of the aircraft noise and measurements of the DC total-field at the MAD sensor when the aircraft is on various headings on the ground to predict what the in-flight noise will be?

Consider the situation where a MAD-equipped aircraft is sitting on the ground on an arbitrary heading. The DC total-field will be some initial value. If the aircraft is re-positioned to a new heading and the magnetometer is positioned over exactly the same spot, and the Earth's field itself has not changed during the time it takes to re-position the aircraft, which of the above 16 terms will contribute to a changed DC total-field? The components of the Earth's field will not be changing so T', L', and V' are zero. Thus only the permanent and induced sources will contribute. However, if the V output stays the same from one heading to another (that is the fluxgate is aligned so that V is vertical and the aircraft is level), then Term 3 will not contribute to the change. This leaves the following terms from the 16-term model that contribute to the change in the DC total-field at the MAD sensor:

$$\begin{aligned}
&\text{Term 1} = C_1 \times T/He \ , \\
&\text{Term 2} = C_2 \times L/He \ , \\
&\text{Term 4} = C_4 \times T \times T/He \ , \\
&\text{Term 5} = C_5 \times T \times L/He \ , \\
&\text{Term 6} = C_6 \times T \times V/He \ , \\
&\text{Term 7} = C_7 \times L \times L/He \ , \text{and} \\
&\text{Term 8} = C_8 \times L \times V/He \ , \qquad [4]
\end{aligned}$$

However, Terms 1 and 6, and Terms 2 and 8, are co-linear because V is constant. This leaves a reduced model with only 5 terms that contribute to the DC total-field changes as the aircraft is re-positioned on the ground. In order to avoid confusion, the model for the DC total-field changes measured on the ground will be re-defined as:

$$\begin{aligned}
&\text{Ground Term 1} = A_1 \times T/He \ , \\
&\text{Ground Term 2} = A_2 \times L/He \ , \\
&\text{Ground Term 3} = A_3 \times T \times T/He \ , \\
&\text{Ground Term 4} = A_4 \times T \times L/He \ , \text{and} \\
&\text{Ground Term 5} = A_5 \times L \times L/He \ , \qquad [5]
\end{aligned}$$

where the A_i are the five unknown coefficients. For a given aircraft heading, the DC total-field measured at the MAD sensor is given by:

$$\text{DC Total-Field} = \text{Earth's Field} + \Sigma \ \text{Ground Term}_i \ . \qquad [6]$$

In order to calculate the five coefficients, it is necessary to measure the DC total-field on at least five different headings. In practice it may be necessary to measure the total field on many different headings in order to reduce the effect of temporal changes in the Earth's magnetic field during the re-positioning of the aircraft.

3. Ground Measurements

3.1 Experimental Setup

The Convair 580 aircraft is equipped with two magnetometers in the left wingpod as shown in Figure 1. The midpoint between the two left magnetometers is beneath the wingtip so it was decided to use the average of the left forward and left aft signals as a "virtual magnetometer" for this trial. I.e.

$$\text{Total-Field} = [(\text{Left Aft Signal}) + (\text{Left Forward Signal})]/2 \quad [7]$$

(This technique has been successfully used for many years with Convair data to create a virtual total-field along the centre-line of the aircraft from the average of the left-forward and right-forward magnetometers. The compensation of this virtual magnetometer is of the same quality as for either of the real magnetometers.)

The ground measurements were conducted at the 14 Wing Compass Rose facility at CFB Greenwood, Nova Scotia. The aircraft engines were running and the aircraft was in the standard "rigged for MAD" configuration. Ground personnel directed the pilots as the aircraft was slowly taxied in a circle, keeping the left wingtip over approximately the same spot on the ground. The circle was repeated 3 times over a period of 10 minutes. CA-Code GPS navigation data was recorded during these circles. Although we intended to use a magnetic basestation to remove the temporal changes in the Earth's field from the ground measurements, hardware problems did not allow us to record the data.

Figure 1. Position of magnetometers on the National Research Council Convair 580 aircraft

3. Ground Measurements
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Figure 1. Position of magnetometers on the National Research Council Convair 580 aircraft.

3.2 Position of the Total-Field Sensor During the Experiment

Figure 2 shows the aircraft GPS track and the calculated position of the "virtual magnetometer" located at the midpoint of the two left magnetometers. Figure 3 shows the distribution of positional errors - that is the actual position of the virtual magnetometer relative to the desired spot on the ground. The average error was 0.60 m; 70% of the measurements lay within 0.8 m and 95% of the measurements lay within 1.2 m of the desired spot.

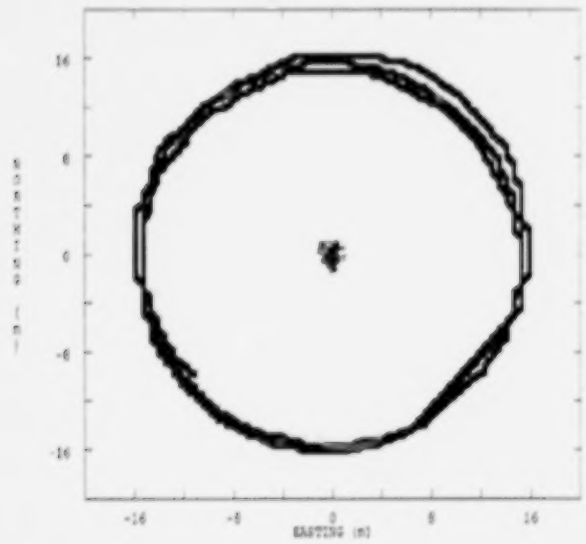

Figure 2. Aircraft track (black) and calculated position of virtual magnetometer (red) during the ground measurements.

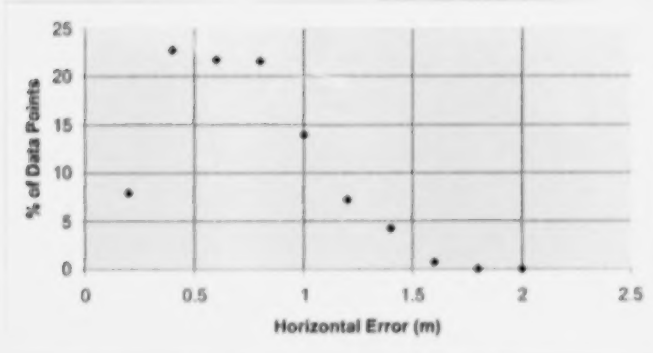

Figure 3. Distribution of horizontal positioning errors for the virtual magnetometer with respect to the desired location.

3.3 Calculating the Five Ground Coefficients

Figure 4 shows the DC total-field measured during the three circles as calculated from Equation [7]. Twenty points were chosen from the circles and a least-squares fit was used to calculate the 5 coefficients A_i. Figure 5 compares the measured DC total-field to the fitted DC total-field calculated from A_i, all of the measured T,L,V, and Equations [5] and [6].

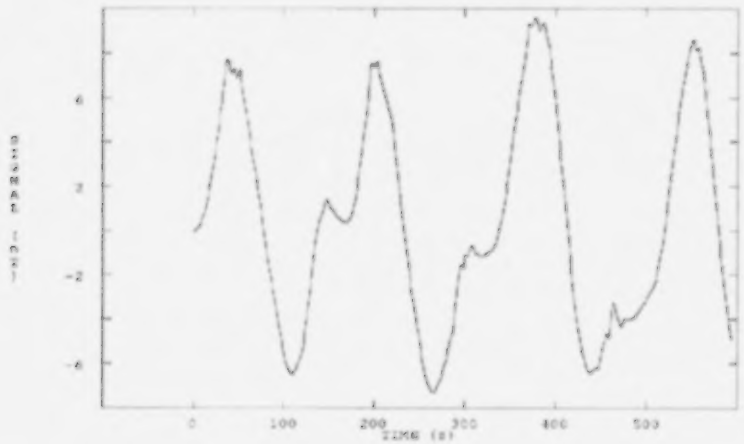

Figure 4. Total-field measured as the aircraft taxied in circles at Compass Rose.

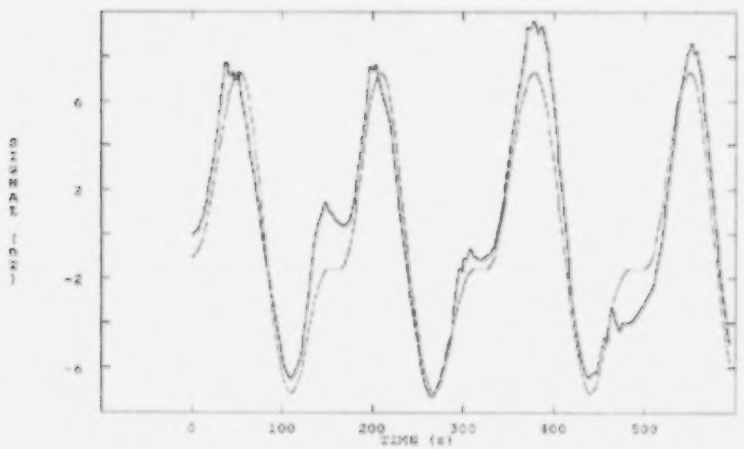

Figure 5. Total-field measured (black) vs fitted (red) for the ground measurements.

Clearly the 5-term model for the aircraft's magnetic interference fits the overall long-wavelength features of the ground measurements, but there are some significant differences as well. These differences may have been caused by the horizontal positioning errors, temporal variations in the Earth's field during the measurements, or movement of the ground personnel who were giving directions to the pilots. Can these same 5 coefficients be used to predict the aircraft's magnetic interference during flight, especially in the MAD passband?

4. Flight Data

The Convair 580 was flown through a set of compensation manoeuvres (pitches and rolls on six headings) on the day after the ground measurements were completed. The aircraft was in the same "rigged for MAD" configuration for the compensation manoeuvres so it is believed that the magnetic state of the aircraft was the same for both the ground and flight measurements.

4.1 Calculating the "Measured In-Flight MAD Noise"

In order to determine if the ground measurements can be used to predict the in-flight noise, it is necessary to calculate what the actual in-flight noise is. To do this, the a normal compensation procedure was applied to the measured T,L,V, and virtual total-field data (average of the left-forward and left-aft magnetometer signals) to calculate the full 18 coefficients C_i of Equations [1a-r]. In this case, both the 18 Terms and the total-field signals were bandpass filtered with a 0.1-0.8 Hz digital filter. The bandpass filtered compensation statistics were:

$$\sigma_{uncompensated} = 0.50 \text{ nT}$$
$$\sigma_{compensated} = 0.031 \text{ nT}$$
$$\text{Improvement Ratio} = \sigma_{uncompensated}/\sigma_{compensated} = 16.1 \ .$$

Once the 18 coefficients were obtained, they were multiplied by the unfiltered T,L,V outputs and summed in order to estimate the aircraft's magnetic interference down to DC. This interference was subtracted from the measured virtual total-field, leaving just the signals due to the underlying geology. This geological signal was visually inspected for residual noise at the manoeuvre frequencies. Because there was very little residual noise at these frequencies, this indicates that the full compensation model accounts for all of the aircraft-generated in-flight noise.

4.2 Calculating the "Predicted In-Flight MAD Noise" from the Ground Coefficients

Next the T,L,V data from the flight and the five ground coefficients A_i were used to generate the terms of Equation [5]. The terms were summed as per Equation [6] to generated an estimate of the aircraft magnetic interference down to DC. Figure 6 compares the measured in-flight aircraft interference to the predicted in-flight aircraft interference without any filtering. Figure 7 compares the 0.1-0.8 Hz bandpass-filtered measured and predicted in-flight MAD noise.

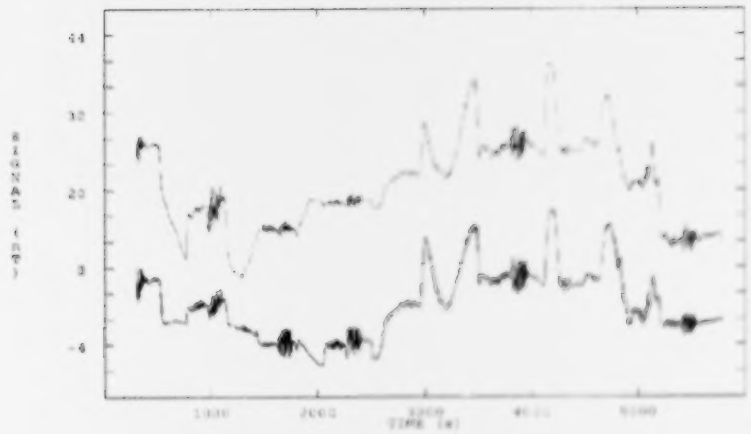

Figure 6. Measured in-flight magnetic noise (black) vs predicted in-flight noise (red). No filtering applied. Vertical offset is for display only.

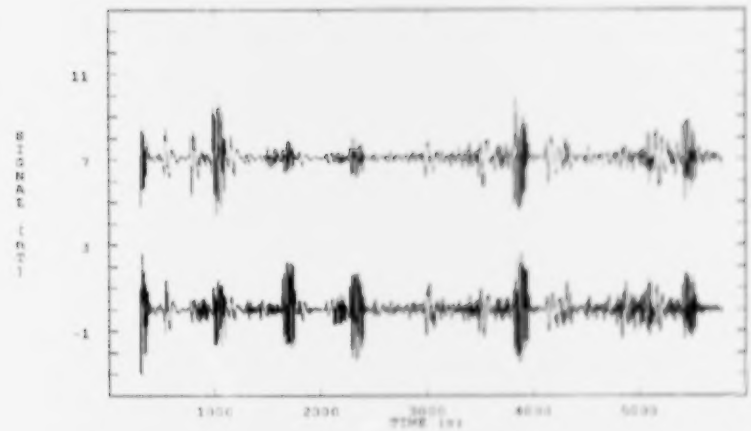

Figure 7. Measured in-flight MAD noise (black) vs predicted in-flight MAD noise (red). 0.1-0.8 Hz bandpass-filtering applied. Vertical offset is for display only.

4.3 Comparison of Measured and Predicted In-Flight MAD Noise

It can be seen in Figure 6 that the low-frequency behaviour of the predicted interference closely matches that of the measured interference but that some differences occur during the turns. This is to be expected as the ground model does not account for any noise due to the term "V/He" or differentiate between the terms "T × V/He" and "T/He" or "L × V/He" and "L/He". These effects will be most noticeable during large banks as the aircraft turns to a new heading. Figure 7 clearly shows that the predicted amplitudes do not exactly match the measured amplitudes for individual manoeuvres either. Again, this is to be expected as the ground model does not account for eddy currents and, because the magnetometers are close to the wings, eddy currents do produce a significant amount of magnetic interference in the Convair. However, the overall statistics of the measured and predicted uncompensated bandpass filtered total-field are:

$$\text{Measured } \sigma_{\text{uncompensated (0.1-0.8 Hz)}} = 0.50 \text{ nT}$$
$$\text{Predicted } \sigma_{\text{uncompensated (0.1-0.8 Hz)}} = 0.47 \text{ nT}$$

Thus the predicted standard deviation agrees with the measured standard deviation to within 6%.

4.4 Accuracy of the Predicted In-Flight Noise vs Number of Points Used to Calculate the Ground Coefficients

Figure 8 compares the standard deviation of the bandpass-filtered predicted noise to the measured noise as a function of the number of data points used to calculate the five ground coefficients. Using only 12 data points, the predicted in-flight noise converges to within a 4-6% of the correct value. The question arises as to why it does not give the correct answer when only 5 data points are used. Again this is probably due to temporal variations in the Earth's field during the ground measurements, small errors in horizontal positioning of the "virtual magnetometer" over the exact same spot on the ground, or movement of the ground crew who were assisting the pilots. Perhaps using more than 10 data points in the least-squares fitting routine, averaged out these effects.

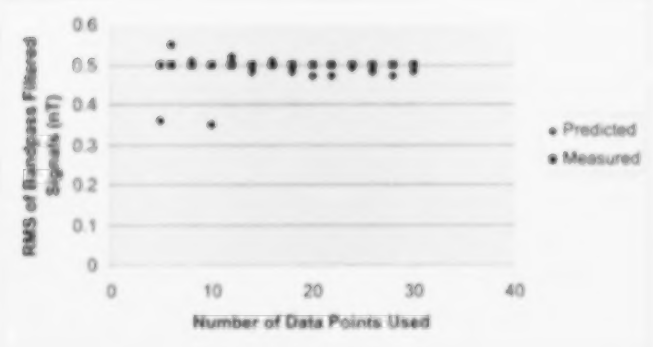

Figure 8. Standard deviation of the 0.1-0.8 Hz bandpass filtered measured vs predicted in-flight MAD noise as a function of number of data points used to calculate the ground coefficients.

5. Potential Applications of the Technique

This quick and inexpensive technique for estimating the in-flight aircraft noise from ground measurements has several applications including:

1) Check after each aircraft refit to ensure that no excess magnetic contamination has been introduced.
2) Monitor signature characteristics of the whole fleet to determine if certain aircraft, or certain systems, are generating excess magnetic noise.
3) Separate noise of electrical origin or control-surface motion from that due to airframe magnetization.
4) Study the effects of "perming up" of aircraft over time and thus properly answer the question of how often compensation manoeuvres should be performed with ASQ-502-equipped aircraft
5) Test the suitability of candidate MHP helicopters as MAD platforms without requiring flight testing.

6. Possible Refinements to the Technique

Although the technique was successfully used to predict standard deviation of the bandpass-filtered in-flight MAD noise on the Convair aircraft, the method of making the ground measurements should be modified for different aircraft. Because the Convair magnetometers are in the wingpods, taxiing in a circle kept the virtual magnetometer close to a single spot on the Compass Rose. However, the MAD sensor is located in the tail boom of the CP-140 so it would be much easier for the pilot to taxi a CP-140 along radial markings on the Compass Rose, stopping for a few seconds when the MAD sensor is over the correct spot. This would require a spotter to contact the pilot when the magnetometer was in the correct location. However, it should take less than 1 minute per measurement so that all ground measurements could still be completed in less than 20 minutes. For helicopters, the same technique of taxiing along radial markings could be used or the helicopter could lift up, turn to a new heading, then descend back to the same spot on the Compass Rose. This method might result in more positioning error than simply taxiing along a radial marking, but it should require less time.

In all cases, a basestation magnetometer should be used to measure the temporal variations in the Earth's field while the ground measurements are performed. Although ideally this would involve measuring both the basestation magnetometer and the aircraft magnetometer with the same data acquisition system, it is probably adequate to use two separate data acquisition systems and time tag the data. As long as the two systems are synchronized to within a few seconds, there should be no problems in removing the temporal variations from the ground measurements.

If the Compass Rose was surveyed to measure the horizontal gradients of the magnetic field at the height of the aircraft magnetometer, then it might be possible to use differential GPS to very accurately determine the position of the magnetometer sensor for each of the measurement points. Corrections could then be applied for slight horizontal offsets of the magnetometer from the desired spot. However, this would require a more complex data acquisition system.

More care should be taken to avoid magnetic noise due to movement of spotters or ground personnel. Taken together, all of these improvements may produce more accurate

predictions of the noise amplitudes due to individual manoeuvres instead of just accurate predictions of the standard deviation of the noise.

7. Conclusions

Ground measurements made at Compass Rose were used to predict the in-flight MAD noise on the Convair 580 aircraft. Although the predicted noise amplitudes did not match the measured amplitudes for individual aircraft manoeuvres, the standard deviation of the predicted in-flight MAD noise in the band 0.1-0.8 Hz agreed with that of the measured in-flight noise to within a few percent. Thus the ground measurements can be used as an indicator of the degree of magnetic contamination in the Convair aircraft.

The predicted heading dependence of the aircraft's DC interference closely matched what was measured. The poorest predictions occurred, as expected, during turns when the effect of the terms not included in the ground model have the most effect.

The in-flight noise prediction converged rapidly and only a small number of ground measurements (12) were required before there was no further improvement in the quality of the prediction.

In order to more easily apply the method to the Canadian Forces fleet of MAD-equipped aircraft, some modifications to the ground measurement methodology have been suggested. A number of potential applications for the method have been identified.

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3. B.W. Leach, *Automatic Aeromagnetic Compensation*, Report No. LTR-69, National Aeronautical Establishment, National Research Council of Canada, 1979.

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In the past, determining the magnetic state of magnetic anomaly detector (MAD)-equipped aircraft required dedicated flight time. It was necessary to perform standard pitch, roll, and possibly yaw manoeuvres to measure the uncompensated Figure-of-Merit in order to determine if the aircraft's magnetic state had changed. This change could have been caused by ferrous material left in the vicinity of the magnetometer during an aircraft refit, replacement of the MAD sensor, or large-scale modifications to the aircraft or its systems.

A new technique using only a few measurements taken on the ground at a magnetically quiet site (e.g. a Compass Rose) has been developed to monitor the magnetic state of MAD-equipped aircraft. The technique, first suggested by CAE Electronics Ltd., was used to model the permanent and induced magnetic sources on the National Research Council Convair 580 aircraft and to predict the in-flight MAD noise. Although the predicted noise amplitudes do not match the measured amplitudes for individual aircraft manoeuvres, the standard deviations agree to within a few percent when calculated over a full set of compensation manoeuvres. Thus the ground measurements can be used as an indicator of the degree of magnetic contamination in the aircraft.

This technique could be adapted to monitor the magnetic characteristics of both the Canadian Forces CP-140 and CH-124B fleet, and to conduct a number of MAD-related experiments at a minimal cost.

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